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Reliable NCO carrier Generators for GPS Receivers

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Abstract—Four strategies for upset protection in NCO (Numerically controlled oscillator) generators are presented and compared in this paper¹. This work is motivated by the increased prevalence of single event upsets due to process/voltage/temperature variations coupled with the increased advancement of CMOS technology. The occurrence of these upsets in the GPS context (the system under the test in this paper) can lead to a loss of the GPS signal tracking, then the corresponding satellite signal must be re-acquired resulting in high energy expenditure and time delay. It can result also in a corrupted position given by the GPS receiver. Results of experiment using a GPS receiver design are presented in this paper to evaluate the performance of proposed methods. This work can be extended and generated to any system using feedback loops information.

I. INTRODUCTION

During the last decades, increased advancement of CMOS technology coupled with process/voltage/temperature (PVT) variations, have made internal upsets on devices more frequent [1], [2]. These upsets manifest as momentary fault in the device's behavior and their occurrence can significantly affect the circuit performance and output states. Therefore, it is extremely important to protect systems from fault's impact to achieve acceptable reliability and maintain low complexity and cost. Fault tolerance has been studied for mobile systems to build mobile devices more robust to transient errors due to PVT variations. For example, the author of [3] proposed some resilience techniques for double-iterative multiple-input multiple-output bit-interleaved coded modulation (MIMO BICM) receivers. These techniques have been realized on different layers of abstraction in order to have a mutual trade-off of system performance, hardware reliability and implementation complexity.

Global Positioning System (GPS) receivers are extensively used in mobile context, and there is motivation to minimize power consumption and maximize battery life in these devices. Fault tolerance has been studied for data fusion in navigational systems that incorporate GPS receivers along with other sensor devices. For example, the authors of [4] consider an intelligent data fusion system to compensate for delayed or erroneous GPS data due to acquisition loss or signal obstruction. In

[5], strategies have been proposed and evaluated for upset protection in Gold sequence generators. Paper [6] presents two approaches to deal with internal logic upsets inside correlation process used in the tracking process of GPS receivers.

GPS receivers use Numerically Controlled Oscillators (NCO) to produce a local copy of the carrier frequency offset (due to Doppler offset) of incoming satellite signals. When the NCO output is corrupted, distance measurements in the GPS receiver are disturbed and this leads to a faulty localization of the receiver. This problem can be mitigated if the NCO is protected. In this context, this paper presents four solutions to make the NCO module more robust to upsets and evaluates those solutions in terms of their performance. This work can be generated for any NCO in feedback loop systems. The remainder of this paper is organized as follows. Sec. II gives detailed information in a compact form about the GPS receiver architecture and rules of NCO generators. Sec. III presents the Triple Modular Redundancy (TMR) method. Sec. IV, V and VI describe three methods using the modular redundancy. Sec. VII provides synthesis and performance results. Finally Sec. VIII offers conclusions.

II. GPS SIGNAL PROCESSING

GPS is the US Global Navigation Satellite System (GNSS) that provides free positioning and timing service. Each GPS satellite broadcasts a navigation message at 50 bits/s using the Code Division multiple Access (CDMA) technology. The analytical expression of the transmitted signal of a satellite k is

$$e_k(t) = c_k(t) d_k(t) e^{(2\pi j f_{L1} t)}$$

, where:

- $d_k(t)$: navigation message of the k^{th} satellite;
- $c_k(t)$: k^{th} Coarse/Acquisition (C/A) satellite code with a Binary Phase Shift Keying (BPSK) modulation (i.e. $c_k \in \{-1, 1\}$);
- f_{L1} : the carrier frequency in the L1 GPS Band (Open Service).

At least four GPS satellites are needed for a GPS receiver to be able to compute the position in time and space. The incoming digital GPS signal in the receiver is first demodulated by a frequency $F_{L1} - F_I$ (F_I represents the intermediate

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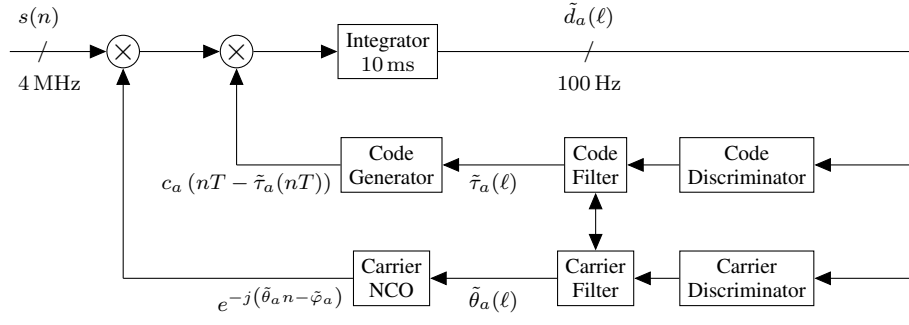


Fig. 1. Generic digital receiver channel block diagram

frequency), and, after a bandpass filter, sampled at a frequency of 4 MHz. The n^{th} received sample $s(n)$ is given by:

$$s(n) = \sum_{k \in \{1..K\}} A_k(nT) d_k(nT - \tau_k(nT)) c_k(nT - \tau_k(nT)) e^{j\theta_k n + \varphi_k} + w(n) \quad (1)$$

where:

- $\theta_k = 2\pi T (f_{d(k)}(nT) + FI)$,
- A_k : Attenuation parameter of k^{th} satellite signal,
- τ_k : Propagation delay between satellite k and receiver,
- $f_{d(k)}$: Doppler frequency of satellite k ,
- $\{1..K\}$: Set of satellites visible at time n ,
- T : Sampling period ($T = 0.25 \mu\text{s}$),
- $w(n)$: additive white Gaussian noise.

For each GPS satellite visible in view, the GPS receiver tries to extract the corresponding navigation message. To do so, there are two essential and sequential processes: the acquisition and tracking process. The acquisition process is the process by which the receiver identifies which satellites are in view. It is a three-dimensional search to determine the GPS satellite identifier (i.e the C/A code c_k associated to the satellite), code phase (represented by $\tilde{\tau}$), and carrier frequency offset due to Doppler effect (represented by \tilde{f}_d). Since satellites are in continuous motion, distances between satellites and the receiver are dynamic. The carrier frequency of the received signal is also constantly changing in time due to Doppler shifts. Therefore, once the acquisition process is accomplished, GPS signals have to be tracked over time.

Each acquired satellite will be tracked by a unique tracking channel. A simplified representation of the channel tracking module is given in Fig. 1. The main objective of each channel tracking module is to extract the navigation message of the corresponding GPS satellite. To do that, using estimated parameters \tilde{f}_d and $\tilde{\tau}$, the GPS receiver produces a local copy of the C/A code (via the Gold Code generators) and the carrier frequency (via the NCO component). Then, a comparison between locally generated signals and incoming signals, using a correlation process and for a period of 10 ms, is made. C/A codes belongs to the family of Gold Pseudo Random Noise (PRN) sequences. Hence codes of all GPS satellites

are orthogonal. Then, the 10 ms integrator output for the a^{th} satellite is defined as,

$$\tilde{d}_a(\ell) \triangleq \sum_{10 \text{ ms}} s(n) c_a(nT - \tilde{\tau}_a(nT)) e^{-j(\tilde{\theta}_a n + \tilde{\varphi}_a)} \quad (2)$$

Thus, a perfect time alignment ($\tilde{\tau}_a = \tau_a$) and a perfect frequency and phase alignment ($\tilde{\theta}_a = \theta_a$ and $\tilde{\varphi}_a = \varphi_a$) implies, according to (1) and (2), that $\tilde{d}_a(\ell) = d_a(\ell)$. The summation over 10 ms in (2) corresponds to the accumulation of 40,000 values ($4 \text{ MHz clock during } 10 \text{ ms}$)². Taking in account the correlation function result, the estimate of the Doppler frequency (\tilde{f}_d) and the delay ($\tilde{\tau}$) is made via discriminators and filters. The carrier loop filter and the carrier discriminator produce an accurate estimate of the Doppler offset of incoming signals while the code loop filter and the code discriminator produce an accurate estimate of the delay offset [7].

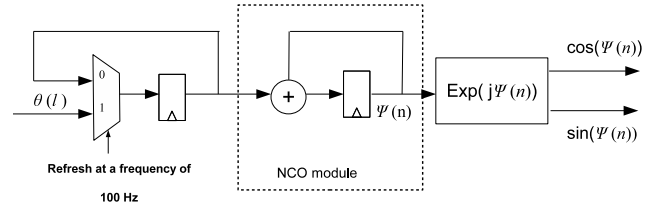


Fig. 2. NCO generator block diagram

Fig. 2 shows a block diagram of the carrier loop NCO and its sine and cosine mapping functions. The NCO carrier receives at its input the estimated Doppler offset value θ . The value of θ remains constant each 10 ms (tracking loops are operating at 100 Hz). If we consider ψ the output of the NCO carrier, ψ is produced each $0.25 \mu\text{s}$ (i.e at 4 MHz) and is defined as

$$\forall n \quad \psi(n) = \psi(n-1) + \theta(\lfloor n/N_s \rfloor) \quad (3)$$

where $\lfloor x \rfloor$ is the floor function of x and N_s is total number of samples generated by the NCO in 10 ms ($N_s = 40000$ in the GPS context). If the NCO outputs are disturbed due to logic internal upsets, then the corresponding carrier frequency

²Each bit of the navigation message have a duration of 20 ms (50 Hz bit rate). Thus, assuming perfect bit timing synchronisation, $d_a(\ell)$ is constant while computing (2)

becomes corrupted, resulting in a loss of the GPS signal tracking. This problem can be mitigated if the NCO is protected by an error corrector method. Next sections will present different methods that can be proposed to protect the NCO carrier from momentary errors.

III. TRIPLE MODULAR REDUNDANCY (TMR)

TMR is a classical solution for fault tolerance in electronic systems [8]. It has been widely used for electronics in the space and nuclear industries to ensure reliable operation [9]. In a TMR system, the original module (the adder + register in this case) is replicated three times, and error correction is achieved by a majority vote operation. We note that there are several configurations, such as one-voter TMR, the triple-voter TMR or the restorative-feedback TMR [10]. In this paper we will use the one-voter and the triple-voter TMR as represented in Fig. 3.

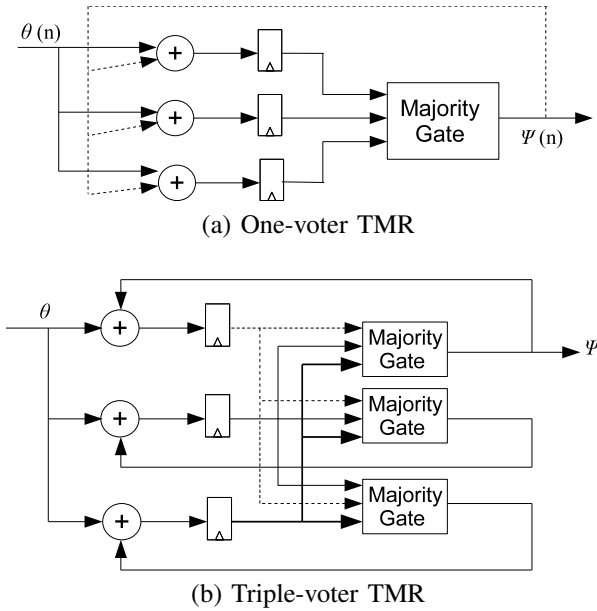


Fig. 3. NCO carrier with TMR protection

If an upset occurs in anyone of the three replicas, the other two replicas can correct and mask the error. But once two of the three replicas fail, an error will be generated in the system and propagated over time. We note also that errors in the voter are extremely harmful for the system because they will not be corrected. To deal with these drawbacks, the triple-voter TMR also triplicate the voters so that a vote error can be corrected in a subsequent circuit stage.

IV. RENDEZ-VOUS CHECKING METHOD (RVC)

In a TMR system, the original module is replicated three times and error correction is achieved by a majority vote operation. In this case area and power consumption increase of more than 300%. To design a NCO tolerant to transient error with low complexity and cost we propose here to use

the assumption that the NCO input remains constant during each 10 ms. So from (3), we can deduce that:

$$\forall \ell \in \mathbb{N} \quad \psi((\ell + 1) N_s) = \psi(\ell N_s) + N_s \theta(\ell) \quad (4)$$

Based on (4), we add to the original architecture (i.e the adder and the register) a correction module composed by a multiplier and adder as configured in Fig. 4. At the end of each 10 ms, the correction module produces a new output (ψ_c) by substituting ψ_c in place of ψ in (4). The Rendez-vous Checking Method will consist on a meeting (Rendez-vous) organised at the end of each 10 ms to check the coherence of values between ψ_c and ψ_o (where ψ_o is the output of the original module given by substituting ψ_o in place of ψ in (3)). Once an incoherence ($\psi_o \neq \psi_c$) is declared, it is ψ_c that will be used later clocks.

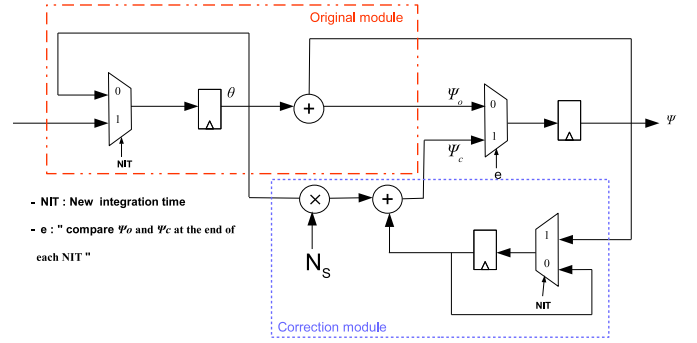


Fig. 4. Rendez-vous checking method configuration

Fig. 5 illustrates how we are able to correct errors occurring when the NCO is operating. However, when an error occurs when the correction module is operating, an uncorrectable failure results in the system. We have to note here that the probability to have a faulty correction module is low once the correction module output is computed during 10 ms.

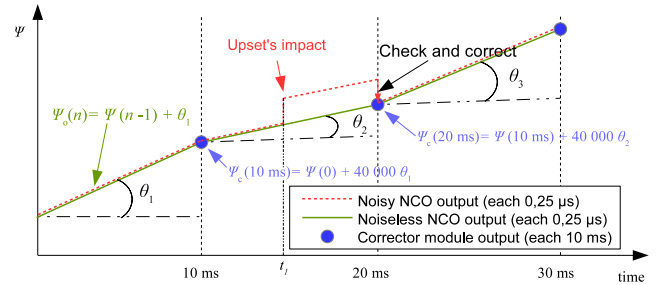


Fig. 5. Correction of errors in RvC method; when an error occurs at time step t_i , it can be corrected at time at 20 ms thanks to the correct output of the correction module.

V. TIME FREEZING METHOD (TF)

In order to make the NCO carrier generator more robust against upset, the original module is duplicated. Then we use a comparator to detect incoherence between replicas output. Let's consider :

- $\psi(n)$: the output of the NCO at time step n

- $\psi_1(n)$: the output of Adder₁ at time step n
- $\psi_2(n)$: the output of Adder₂ at time step n

Once one of the two adders are faulty (i.e $\psi_1(n) \neq \psi_2(n)$, $e = 1$), the correct previous output of the NCO (i.e $\psi(n-1)$) is used to feedback adders as shown in Fig. 6.

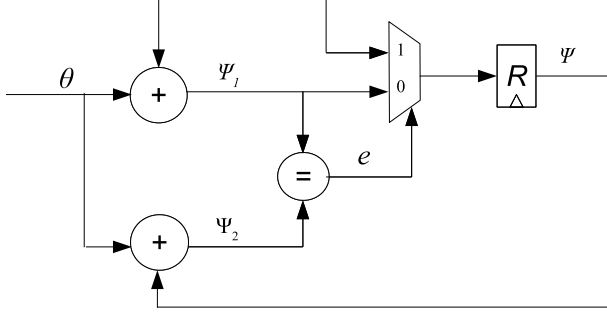


Fig. 6. Time Freezing Method configuration

However, if the register R is faulty, the TF configuration fails and errors will propagate over time in the tracking loops.

VI. ROBUST TIME FREEZING (RTF) METHOD

To deal with TF method drawbacks we propose in this method to triplicate the register as shown in Fig. 7. The register R in Fig. 7 is used to store the NCO output and to feedback adders with the last correct output value of the NCO when an incoherence between adders output is detected. As for the TMR 3 Voter, any simple error can be detected and corrected in the RTF configuration.

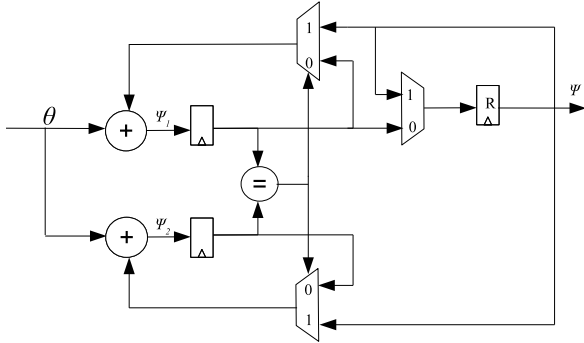


Fig. 7. Robust Time Freezing Method Configuration

VII. PERFORMANCE RESULTS

In this section, we first define the method to assess the quality of a GPS with a noisy NCO carrier. Then, all of the described methods were evaluated and compared.

A. Quality of a noisy GPS receiver

The methodology used to evaluate the quality of the proposed method is threefold:

- Use the front end of a GPS receiver to store incoming GPS signal $s(n)$ over a significant period of time (few minutes).

- Process the stored input GPS signal with a reference noiseless GPS receiver [11] to generate the set of successive estimated positions $X(p)_{p=1..Q}$.
- Replace the noiseless GPS receiver with a noisy GPS receiver and process a Monte-Carlo simulation processing N times the stored incoming GPS signal to generate sets of noisy position $\tilde{X}^i(p)_{p=1..Q}$, $i = 1..N$.

Then, we can study the link between the model of error injection, the hardware used to mitigate errors and the statistical difference between the noiseless GPS position X and the noisy GPS position \tilde{X} .

1) *model of noise*: The model of noise used in this paper is very simple. For each active tracking module, every output of the NCO module is assume to be exact with a probability $(1 - p)$ or to be faulty with a probability p . In case of faulty result, a random random is uniformly drawn between 0 and 2π to replace the exact value.

2) *Metric to evaluate the quality of the noisy GPS receiver*: Two metrics are used to evaluate the quality of the noisy GPS receiver. The first one is the Mean Squared Error (EQM) defined by:

$$\text{EQM}(p) = \sqrt{E(|X - \tilde{X}|^2)} \quad (5)$$

where p is the probability of the upsets' injection model (noise) at the output of the integrator 10 ms. This parameter gives us an idea about how many meters, on average, the position given by the noisy GPS is far from the position given by the reference GPS. The second parameter is:

$$f(r, p) = \Pr(|X - \tilde{X}| > r) \quad (6)$$

Given the probability of error injection, p , $f(r, p)$ reflect the probability that the noisy GPS receiver compute a distance at a distance greater than r meter from the noiseless GPS receiver.

B. Evaluation Methods

All of the described methods were evaluated in term of EQM and probability of an alignment of the reference position as defined in (5) and (6). Fig. 8 compares the mean square squared error (EQM) of different method. As we can see from this figure (Fig. 8), Rendez-vous Checking Method provides us a very important result ($\text{EQM} < 10$ m) for the low error probability but it lose its efficiency for the higher error probability. Time Freezing Method and Robust Time Freezing Method correction is more efficient than the TMR one voter and they are very close to the TMR 3 voter. For example, for a probability of upsets up to $p = 10^{-2}$, RTF method gives an error of the position of about 10 meters, 2 meters more than the EQM for the TMR-3 Voter method. In Fig. 9 and Fig. 10 we fix the probability of upsets ($p = 10^{-1}$, for $p = 10^{-2}$ respectively) and we try to compute the probability to be far from the reference position. For instance when $p = 0.01$, the probability of been 10 m far from the reference position goes from 0.42 (No correction mechanism is added to the NCO) to 0.01 using the TF method.

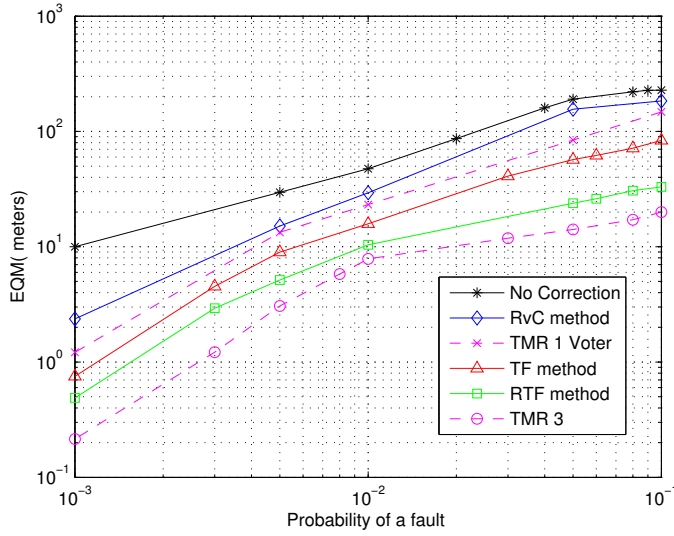


Fig. 8. $EQM = f(p)$; When $p = 10^{-1}$, EQM goes from 50 meters to an error in the position less than 1 meter using the TMR 3 Voter method.

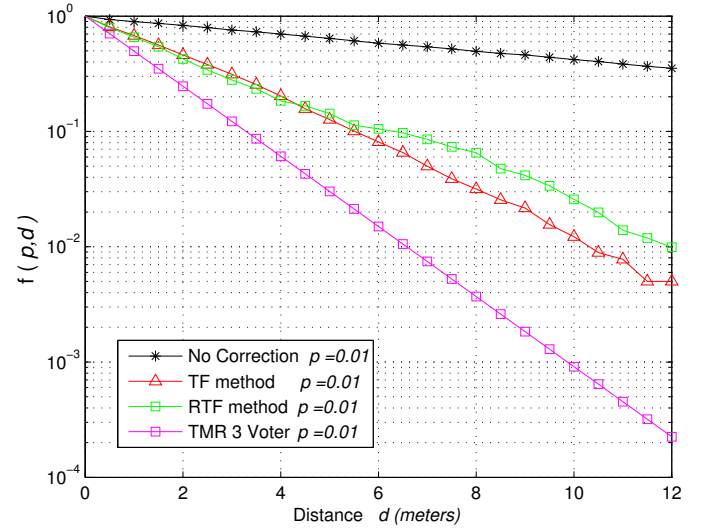


Fig. 10. The probability of the removal (in meters) from the reference position when $p = 10^{-2}$

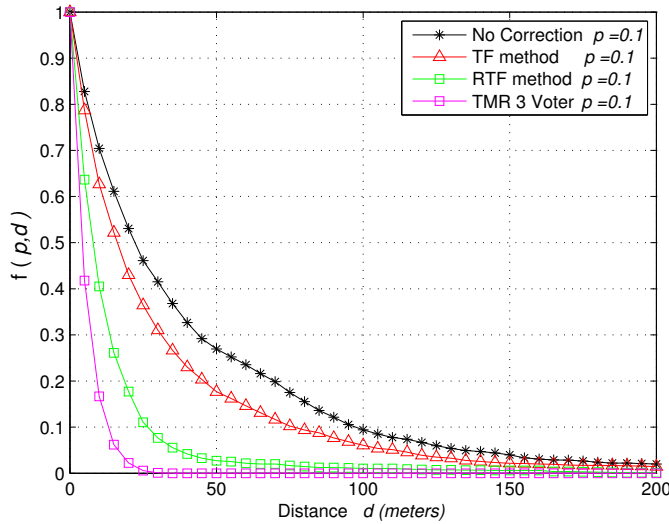


Fig. 9. The probability of the removal (in meters) from the reference position when $p = 10^{-1}$

VIII. CONCLUSION

Our results show an improvement in the probability of the removal from the reference position and in term of EQM with each methods introduced previously. For a small upset probability, Rendez Vous Checking method provides an acceptable reliability for a low cost configuration. For a high upset probability, Robust Time Freezing and Time Freezing method provides the big interest for reducing errors in the NCO carrier.

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